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STUDY ON CHARACTERISTICS OF THREE-DIMENSIONAL GRANULAR MESO-RECONSTRUCTION OF COAL GANGUE ROADBED[1]

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The dynamic evolution process of the coal gangue particles' core retention phenomenon in the process of crushing under stress, the evolution law of grading and the corresponding microscopic mechanical characteristics after continuous particle crushing are analyzed. The meso-level which reveals deformation phenomena of granular materials under the action of external loads is highly complex. At the qualitative level, the static compaction process of coal gangue samples can be roughly divided into three stages: initial compaction stage, compaction and crushing stage, and crushing (compaction) stage. It is proved that the interaction of lateral confined unidirectional compression of granular materials is mainly compression.

Keywords: coal gangue roadbed, particle flow, mesoscopic reconstruction, particle breakage

1. Introduction

As industrial solid waste, large quantities of coal gangue had been used to fill roadbeds, achieving cost reduction and resource utilization (Editorial Department of China Journal of Highway and Transport, 2021; Zhu *et al.*, 2018). After compaction, the strength and stiffness of gangue roadbed would increase, but for gangue with serious coarse particle crushing the particle crushing phenomenon caused by compaction may have a negative effect on its mechanical properties. Coarse particle breakage can promote particle rearrangement. As a result, the pore ratio would decrease and the structure becomes more compact, so the coal gangue fill body would be more mechanically stable. However, excessive compaction would lead to a continuous increase of particle breakage, the "interparticle bite effect" of the coarse grain material would be weakened due to continuous refinement of the material.

The macroscopic mechanical behavior of coal gangue particle samples would be affected by strength of microscopic particles, bonding strength between particles, particle size, shape, arrangement and compactness, etc. Therefore, it is a very complex issue to study mechanical properties of granular materials by means of micro-macro combination. The scholars at home and abroad have conducted a lot of research using theoretical and numerical analysis methods (Bai *et al.*, 2016; Zhang *et al.*, 2019). For example, Xue *et al.* (2018) proposed a discrete element

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numerical test method which adopted spherical numerical samples. By directly controlling the boundary stress of the specimen, the magnitude and direction of three principal stresses could be controlled arbitrarily, which could be achieved in many physical experiments. It was possible to realize complex stress paths that could not be achieved in many physical experiments. Li and She (2018) simulated an indoor single-particle compression test of rockfill based on a numerical model to verify the correctness and rationality of the numerical model, and simulated and predicted the single-particle strength of large-size rockfill to highlight the advantages of the numerical test. Based on the established numerical model, the single particle strength distribution characteristics of the rockfill with the same particle size and different shape characteristics were simulated. Wang (2013) simulated compression characteristics of coal gangue using the contact connection constitutive model of the three-dimensional particle flow method and reproduced its complex nonlinear constitutive relationship. A single grading scheme and Talbot theoretical grading scheme were designed, and the graded particle model was generated by Fish language. The triaxial compression test process of gangue was numerically simulated, and the stress-strain curve, volume-strain curve and microcrack development curve under different confining pressures were compared. The strength and deformation law of gangue samples with different grades from the meso-view were verified. Wang *et al.* (2019) carried out a triaxial drained cyclic shear test on calcareous sand of a reef island. The influence of confining pressure, cyclic stress ratio and cyclic vibration time on the development process of a calcareous sand particle crushing was studied.

After rolling coarse particles of coal gangue subgrade on site, it was found that there exists a phenomenon of "core retention" in the coarse particles. That is, the periphery of coarse particles is broken and fallen off seriously, and the middle part is basically not damaged. The middle core retention area still retains the original particle properties and the compactness above the vibration pressure impacts the energy threshold. It retains rock characteristics, has a high compressive strength and provides most of the subgrade bearing capacity. In the transition expansion area, in the later stage of vibration compression, the strength is lower than that in the middle retention area. After a continuous energy impact, microcrack propagation occurs. It follows the Moore-Coulomb (M-C) damage criterion. When the stress reaches the shear stress state of the material, it presents a failure development trend in the outer edge remodeling area. The cohesive force of particles is lost, and the coarse particles develop into fine particles, and the cohesion is close to zero. At the same time, the subgrade is rearranged with the existing fine particles in the surrounding area, which generates new compactness of fine particles and fills the gap of coarse particles, thus improving the strength and stability of the subgrade under the action of static pressure (Xu *et al.*, 2018).

With the rapid development of computer technology, it provided an effective numerical method to calculate the mesoscopic and mechanical properties of particles. The discrete element method has been used to study the structure of particle sand mechanical behavior of materials with a meso-constitutive model, which has been widely used and achieved significant scientific results (Fu *et al.*, 2018; Yan *et al.*, 2019; Zhang *et al.*, 2016; Wu *et al.*, 2015; Chen, 2018; Lei *et al.*, 2017). The particle flow theory is adopted to generalize the solid particle material into a particle unit, which has been combined by cementation of the particle between point-to-point, point-to-surface, and surface-to-surface. It provided an effective way to study crushing particles and their mechanical response and a mechanism from the mesoscale (Yu *et al.*, 2017; Zhou and Song, 2016; Zhao *et al.*, 2015, Bian *et al.*, 2020; Cong *et al.*, 2015).

The main research content of the above-mentioned scholars is theoretical and experimental research. The discrete element constitutive model has been perfected from the point of view of test and theory, which has played the role of paving the way for the research of this paper. But at the same time, it can be seen that the above-mentioned scholars have made less research in the engineering practice. The research in this paper is based on the research experience of the predecessors, focusing on the study of the special material of coal gangue in the engineering application, the unique phenomenon of particle nucleation. The simulation research is carried out by using the discrete element calculation theory, studying the special engineering characteristics of the coal gangue particles under the action of compaction, such as particle fragmentation, microscopic porosity change, gradation evolution, etc., which complements the research of the predecessors and promotes the development of the theory to the engineering application.

A three-dimensional model of coal gangue particles with specific gradation was established by a particle flow computer program. The dynamic evolution process of "core retention" in coal gangue particle crushing under stress was carried out. The stress, pore structure and fracture evolution characteristics of the coal gangue subgrade during compaction were studied. Mechanical transfer would occur at the coarse and fine contact interface of coal gangue particles. It is of great theoretical significance to study the mechanical effectiveness transfer law of the point-to-surface composite interface of coal gangue from different particle contact modes such as point-to-point, point-to-face and face-to-face.

2. Model establishment

Under the normal energy level, the effect of vibration crushing the coarse coal gangue particles is mainly positive, that is, the strength increase caused by a decrease of the void ratio is dominant. Under a reasonable vibration pressure and static pressure, the strength would not decrease due to compaction.

The three-dimensional model size of coal gangue was 300 mm×300 mm×300 mm, the ratio of sample size to maximum particle size was 5, the influence of the boundary effect could be basically eliminated, as shown in Fig. 1. In the three-dimensional model after compaction, the number of parent particles is 5437, particles above 20 mm in the 3D model were considered as crushable particles, parallel bonding was applied according to the discrete element method, particles below 20 mm were still simulated as rigid particles. The number of particles (including subparticles) in the final three-dimensional model was 97969.

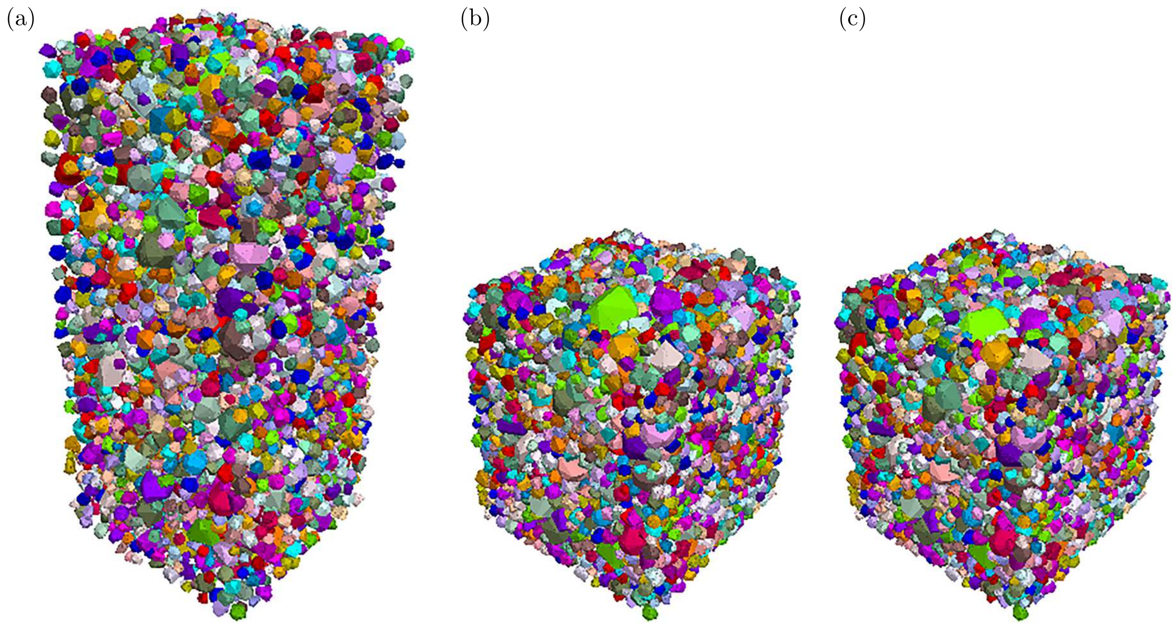

Fig. 1. 3D models of coal gangue: (a) release particles, (b) self weight settlement, (c) compaction

3. Parameter value and loading method

The particle density in the coal gangue sample was 2720 kg/m^3, the local damping was taken as 0.70. The parallel bonding model was set up between the subparticles in the parent particles of coal gangue. The value of parallel bonding parameters was determined according to the experience, as shown in Table 1.

Table 1. Characteristic parameters of the coal gangue samples 3D mesoscale model

Parallel bond model	Mesoscopic parameters	Unit	Value
Linear contact part	Meso elastic modulus	Pa	$1.0 \cdot 10^8$
	Stiffness ratio	–	1
	Coefficient of friction	–	0.50
Bonding part	Meso elastic modulus	Pa	$1.0 \cdot 10^8$
	Stiffness ratio	–	1
	Micro tensile strength	Pa	$1.0 \cdot 10^6$
	Microcosmic cohesion	Pa	$2.0 \cdot 10^6$
	Micro internal friction angle	deg	45

The contact model between parent particles was set as linear, and specific parameters were taken according to the parameters shown in the "linear contact part" in Table 1.

When loading gangue samples, the crushing development of the gangue samples under loading conditions was mainly studied, and normal displacement constraints were set on the bottom and four sides of the gangue samples. A certain normal velocity was applied to the top wall of the model to compact the coal gangue sample in one direction, and the specific velocity was $v = 0.1$ m/s. This speed was generally much higher than that in laboratory tests, but the calculation time step in the numerical model was generally $1 \cdot 10^{-7}$ s/step, that is, the displacement of the wall in each calculation time step was $1 \cdot 10^{-8}$ m, which was small enough compared with the particle size. According to the calculation analysis and experiencey, if the loading rate of $v = 0.1$ m/s is adopted, the calculation results will not be affected, and if the loading rate is too small, the calculation time will be very long and the efficiency seriously affected.

4. Study on the characteristics of three-dimensional meso-remolding of gangue roadbed

4.1. Study on macroscopic deformation characteristics of three-dimensional particles of the coal gangue subgrade

The macroscopic deformation characteristics of coal gangue samples under static loading were mainly characterized by the displacement of particles. The displacement distribution characteristics of particles in the coal gangue samples under different axial strain conditions are shown in Fig. 2, clearly indicated the macrodeformation of the samples.

According to Fig. 2, the displacement distribution of particles in the coal gangue sample showed the characteristics of layered distribution, that is, the maximum displacement of particles at the top was about 7 cm, and the displacement of particles at the bottom was close to 0 under the influence of the constraint of normal displacement of the bottom boundary. The particle displacement decreased rapidly with a decrease in the height of the specimen, which conformed to the general law of the unidirectional confining compression deformation distribution.

At the meso-level, the particle displacements showed characteristics of an uneven and staggered distribution under the influence of local particle sliding, crushing and filling, which revealed

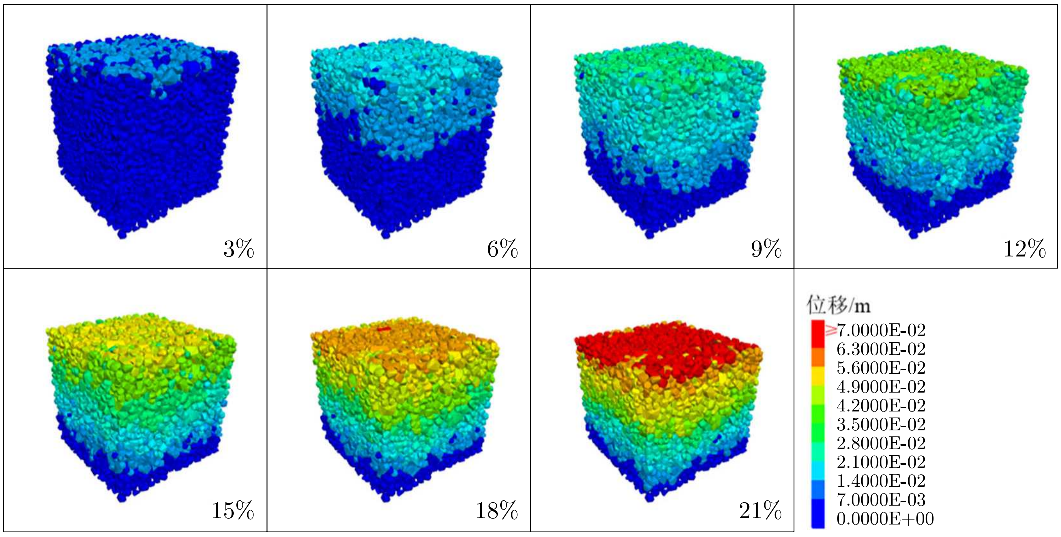

Fig. 2. Macroscopic displacement distribution characteristics of gangue samples under different axial strain condition

a highly complex deformation phenomenon of granular materials under the action of an external load.

4.2. Study on three-dimensional particle micromechanical properties of coal gangue subgrade

The stress-displacement curve of a granular sample in the process of static compaction is an important index to describe static compaction characteristics of the granular sample. Among them, the stress is the force of the granular sample acting on the top wall, and it can also be regarded as the reaction force of the wall acting on the sample under static conditions. The strain reflects the movement distance of the top wall of the sample during the loading process. The stress-strain curve of the gangue sample during the static compaction process, as showed in Fig. 3, shows strong nonlinear characteristics.

According to the calculation results in Fig. 3, it can be seen that the meso-mechanical response of granular samples in the process of static compaction could be roughly divided into three stages at the qualitative level, as follows:

(1) Initial compaction stage: the typical feature of this stage is that the axial strain increases rapidly and the axial stress remains at a low level. Its mechanism is that the compactness of the coal gangue sample is relatively small at the initial stage of loading. Under the action of the external load, the main micro movement of coal gangue particles is particle slip, the crushing phenomenon is not obvious, and the macro performance is the increase of sample compactness.

(2) Compaction and crushing stage: the compactness of the gangue sample increases to a certain extent, and the intergranular interaction is more prominent, so the particles are difficult to slip relatively. At this time, under the action of the external load, the stress level borne by gangue samples rises rapidly, resulting in the breakage of coal gangue particles in local positions. Macroscopically, the stress-strain curve of gangue samples is nonlinear.

(3) Crushing (strong compaction) stage: the compactness of the gangue sample is relatively high, and its ability to bear the external load is further strengthened. Under the influence of high compactness, the macroscopic stress-strain curve of the gangue sample is approximately linear. Due to the high stress borne in the sample, the crushing of particles is more significant, which directly affects the macroscopic performance of the stress-strain curve.

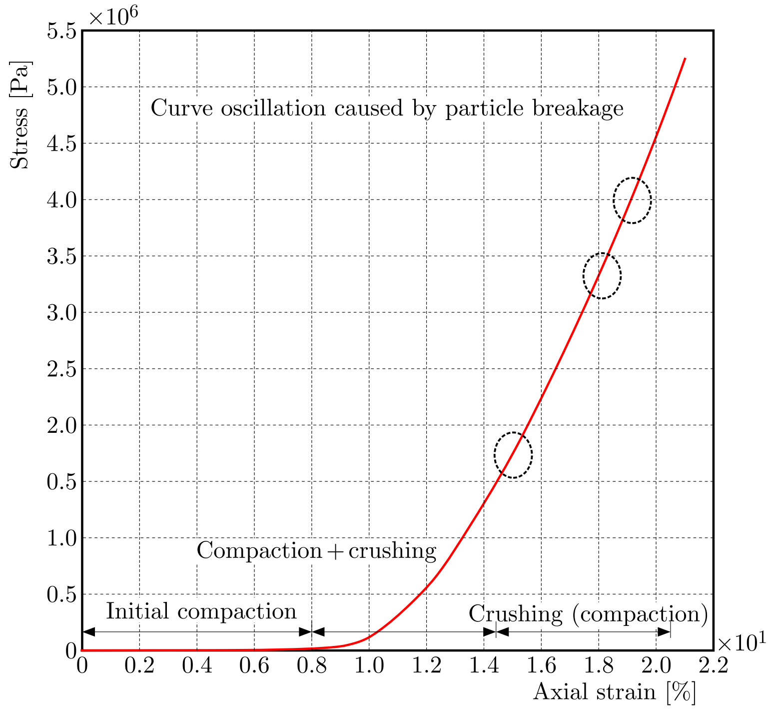

Fig. 3. Stress-strain curves of gangue samples during the static loading test

For example, the stress-strain curve of gangue samples shows characteristics of oscillation in local positions due to the loss of local bearing capacity caused by the particle crushing.

4.3. Study on three-dimensional particle porosity evolution characteristics of coal gangue subgrade

Porosity is an important index to characterize the degree of compactness of granular samples. Since the volume of solid particles in the coal gangue sample is almost unchanged, the porosity of the sample depends directly on the macroscopic volume of the sample. Specifically, under the action of the external load, the macroscopic volume compression deformation of coal gangue samples is mainly caused by the compression of internal voids or filling by coal gangue particles. The curve of porosity variation with axial pressure in the static compaction process of the coal gangue sample is shown in Fig. 4.

The results of Fig. 4 show that at the initial stage of loading, due to the large initial porosity of the gangue sample, the bearing capacity of the sample is low. When the external load increases slightly, the porosity of the sample decreases rapidly. At this time, the microscopic mechanical behavior of the gangue particles in the sample is mainly manifested as particle slip and filling. In the middle and late loading stage, the compactness of the coal gangue sample is relatively high, when the axial pressure increases further, the rate of porosity decline gradually decreases, and finally shows the characteristics of the nearly linear decline.

Particle breakage is a typical micromechanical response characteristic of bulk samples under the external load. In the calculation, the parent particles of coal gangue were bonded by several subparticles. In the particle flow program, bond fracture will produce microcracks, so by analyzing the development of microcracks, we can also intuitively show the crushing situation of coal gangue particles.

The development of internal cracks in the coal gangue sample model under different axial strain conditions is shown in Fig. 5, in which the red circle represents microcracks and the green block is coal gangue particles. In order to study the location of microcracks, the coal gangue

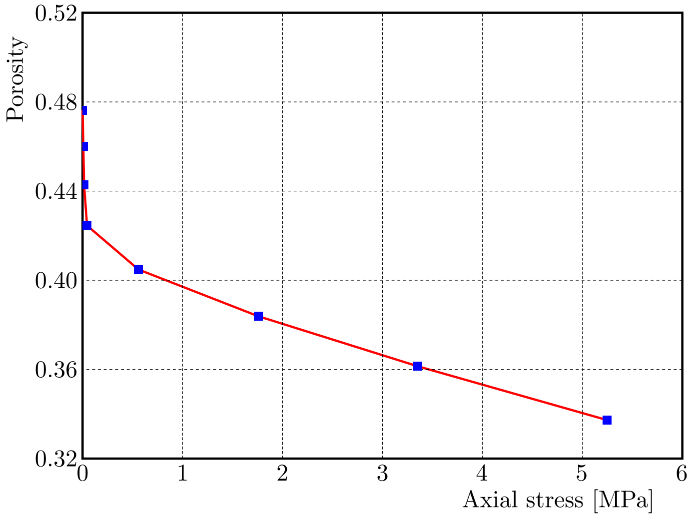

Fig. 4. Evolution law of gangue samples porosity

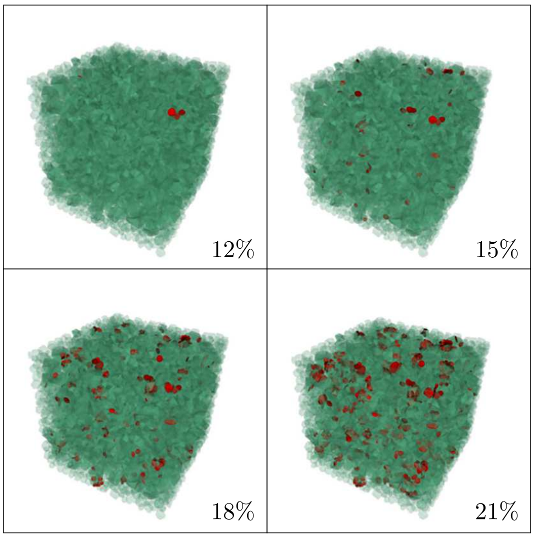

Fig. 5. Crack development of gangue samples under different axial strain conditions

particles in Fig. 5 were treated with transparency. Based on the results of numerical calculation, microcracks begin to appear when the coal gangue sample was loaded to the axial strain of 12%. The development of microcracks under axial strain of 12% and above in Fig. 5 was extracted for further study.

In the calculation and analysis, it was assumed that the coal gangue particles above 20 mm could be broken, and they were randomly and evenly distributed within the scope of the model. The internal microcracks of the coal gangue sample model generally show characteristics of a random and uniform distribution during loading. The evolution law of the number of microcracks in the coal gangue samples with axial strain is shown in Fig. 6. When the axial strain was less than 12%, the number of microcracks was 0, indicating that the gangue particles were not broken. When the axial strain reached 12% and continued to increase, the number of microcracks increased rapidly, indicating that the gangue particles were seriously broken.

In order to further analyze the crushing problem of particles in coal gangue samples, a single particle under different axial strain conditions was taken as the research object. The crushing development of certain particles in the gangue sample is shown in Fig. 7, different coal gangue particles are distinguished by color.

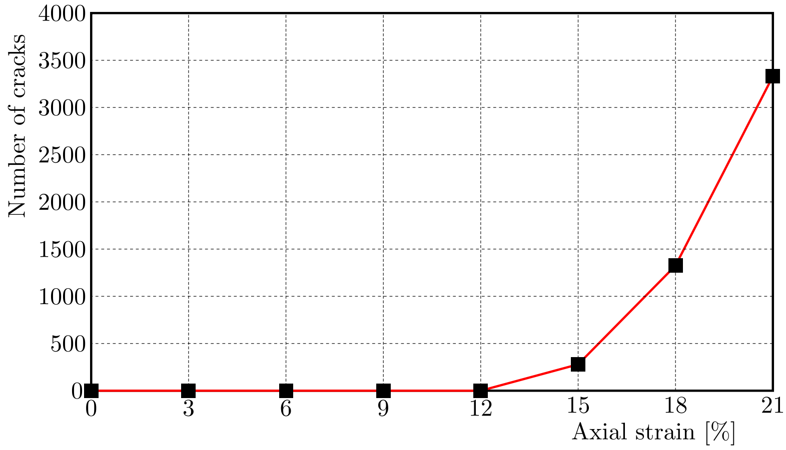

Fig. 6. Evolution law of cracks quantity in gangue samples

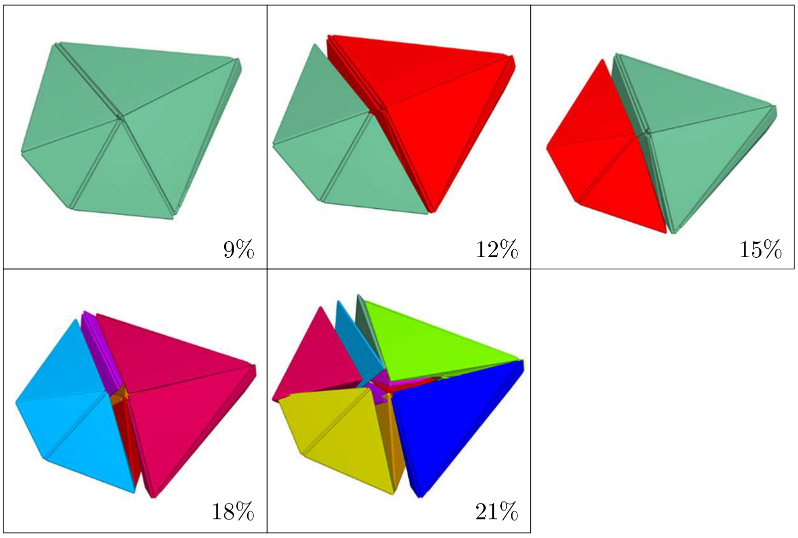

Fig. 7. Fracture development of a single grain in gangue samples

According to the calculation results in Fig. 7, when the axial strain was 9%, the coal gangue particles were not broken and still maintained integrity. When the axial strain was 12%, the gangue particles were broken and divided into two independent secondary gangue particles. When the axial strain was 15%, the particle was still broken into two secondary particles without further development. When the axial strain was 18%, the breakage of the particle was further intensified, and the number of secondary particles formed after breakage further increased. When the axial strain reached 21%, the breakage of the gangue particles was very serious, and the initial intact gangue particles were broken into a series of secondary particles with relatively small size.

When the parent particle of breakable coal gangue was established, the minimum size of its internal subparticle was 0.5 times of the parent particle. For 60 mm coal gangue particles, the size of its internal subparticles was 30 mm, which limited the sensitivity of the coal gangue particle model to identify particle breakage to a certain extent, that is, for 60 mm parent particles, only the breakage of subparticles with the size of 30 mm and above can be identified in the calculation, and the breakage of particles with the size less than 30 mm cannot be simulated.

4.4. Study on three-dimensional particle gradation evolution and crushing rate characteristics of coal gangue subgrade

Particle breakage would appear under a loading in coal gangue samples, the coal gangue particles with larger size would be broken into several secondary coal gangue particles with smaller size, resulting in a decrease of the content of coarse particles and an increase of fine particles in the sample, changing the particle grading relationship of the coal gangue sample. The content change of each particle size section during loading is shown in Fig. 8.

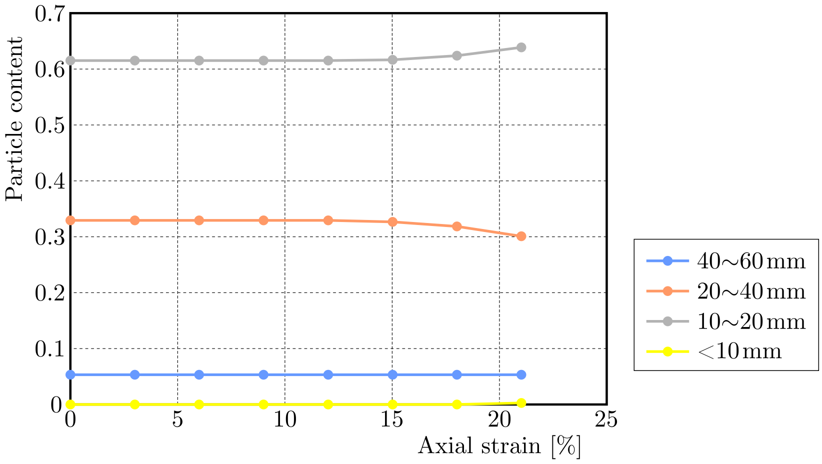

Fig. 8. Changes in the particle content of different grain size during the loading procedure

According to the analysis in Fig. 8, the particle content in the 20-40 mm size section decreased, indicating that the particles in this size section were obviously broken. The particle content in the 10-20 mm particle size section increased, which is mainly due to that larger size particles broke into several smaller particles. In addition, the particle content in the size section of 40-60 mm and below 10 mm also changed slightly, but it was not very obvious.

Through the change of particle content in each particle size section of the coal gangue sample, the crushing condition of the sample can be quantitatively characterized. In this calculation, the Marsal crushing rate was used to describe the particle crushing of coal gangue samples. Through statistical analysis of the variation of the particle content in each particle size section, the variation law of the crushing rate of the coal gangue sample with axial strain can be obtained.

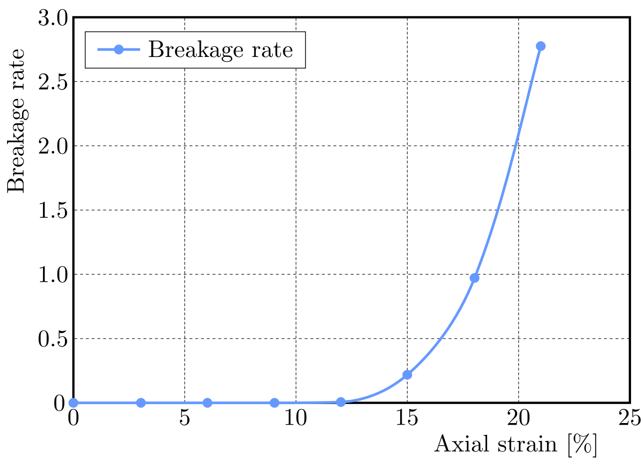

Fig. 9. Evolution law of the gangue samples broken rate

Based on the results shown in Fig. 9, the coal gangue sample began to break when the axial strain was 12%, and with the increasing axial strain, the breakage rate of the coal gangue sample rose rapidly, indicating that the breakage degree of the coal gangue sample gradually strengthened.

For granular materials, the meso-fabric mainly describes the force chain network and its basic characteristics under load bearing conditions. It contains two aspects, namely, the contact directions and the distribution characteristics of contact forces in the force chain network.

Figure 10 reflects the evolution law of the force chain network of the coal gangue sample model under loading conditions revealed by the calculation results, in which the contact in the force chain network is represented by a short line of finite length, and thickness of the line is directly proportional to size of the contact force. In addition, the color of the line corresponds to the size of the contact force of a certain magnitude.

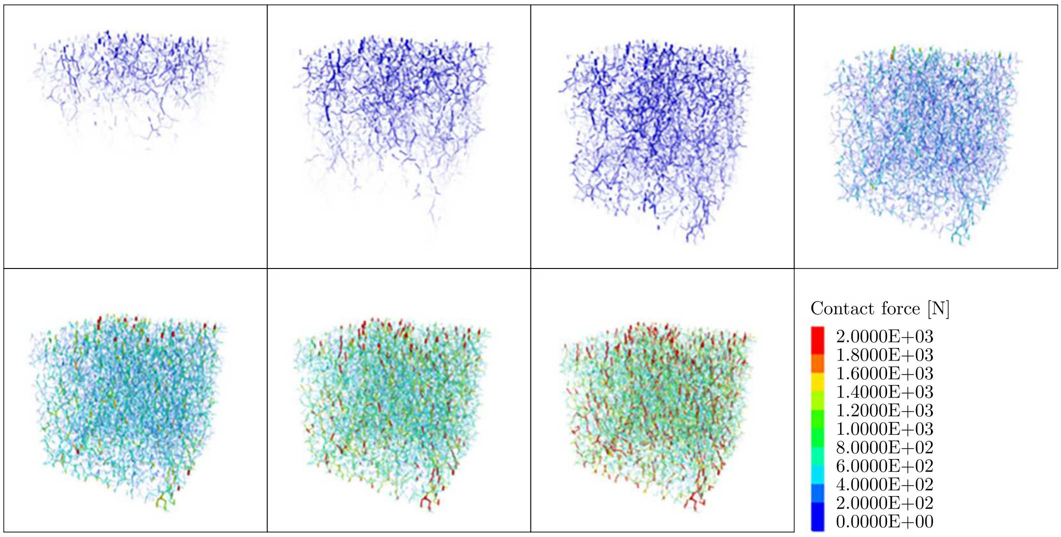

Fig. 10. Evolution law of the force chain network of gangue models

By analyzing the results in Fig. 10, it can be seen that in the bulk sample, with the continuous loading, the number of contact between particles in the model keeps increasing, reflecting an increase of the compactness of the model. On the other hand, the content of strong chain (i.e. contact with force exceeding a certain value) in the model also increased, which reflects the strengthening of the bearing capacity of bulk samples.

In order to further analyze the distribution law of the force chain network in the coal gangue sample model, the normal force (with pressure as positive) and tangential force between coal gangue particles in the calculation model were counted respectively, and the probability density distribution of the contact force was calculated and analyzed. Figure 11 shows the distribution probability of the normal and tangential force between particles of the coal gangue sample under axial strain of 21%. To facilitate the understanding of the meaning shown in Fig. 11, the label $(500, 74.89)$ in the figure is taken as an example, that is, the number of contacts with the normal force less than 500 N accounts for 74.89% of the total number, and so on.

According to the results shown in Fig. 11, for the normal force, although the maximum contact force in the gangue sample model reached about 4100 N, most were below 900 N (accounting for about 90%), which reflects high heterogeneity of the force chain network of bulk samples. Similarly, the maximum value of the tangential force was about 1750 N, but most of the tangential force values were below 350 N. In general, in the force chain network of coal gangue samples, the normal force is much greater than the tangential force, which also demonstrates the basic view that the compression is mainly in the process of confined unidirectional compression.

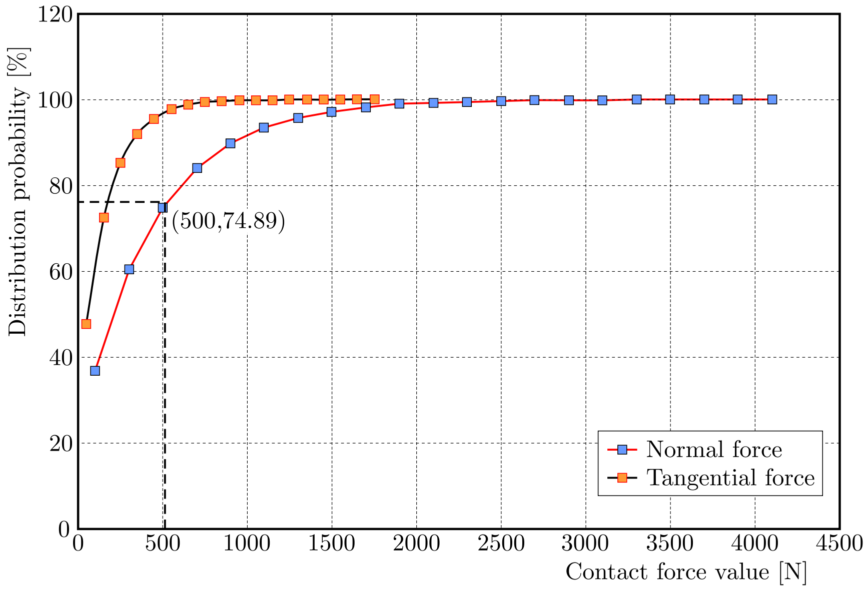

Fig. 11. Probability density statistics of distribution of the contact force

5. The engineering application

G2 expressway reconstruction and expansion project, design speed 120 km/h. The integral roadbed is widened to 42 m, and width of the newly built single separated roadbed is 20.75 m. One section of roadbed was filled with coal gangue industrial waste residue. The site coal gangue had the following characteristics:

(1) The coal gangue had been stored for about 40 years.
(2) The distribution of coal gangue was uniform.
(3) The material source was abundant, with on-site storage of about 1.07 million m^3.
(4) Coal gangue had undergone fully spontaneous combustion.
(5) The effective distance between coal gangue and highway is short, which has the advantage of convenient transportation (Fig. 12).

Fig. 12. On-site coal gangue yard

Coal gangue was used as the subgrade filler on site. During rolling, the particles were seriously broken and the particle gradation changed. The settlement difference method was adopted to control the compaction quality. Before and after each compaction of the subgrade, the elevation of the embedded steel plate in each section shall be measured by a precise instrument. The elevation difference between before and after compaction is the compaction settlement difference.

Figure 13 shows that the settlement difference decreased exponentially with an increase of rolling times. According to the data fitting equation, it can be concluded that

$$y = 74.86\mathrm{e}^{-0.701x} \qquad R^2 = 0.9884 \tag{5.1}$$

Among them, y – settlement difference [mm], x – rolling times [n].

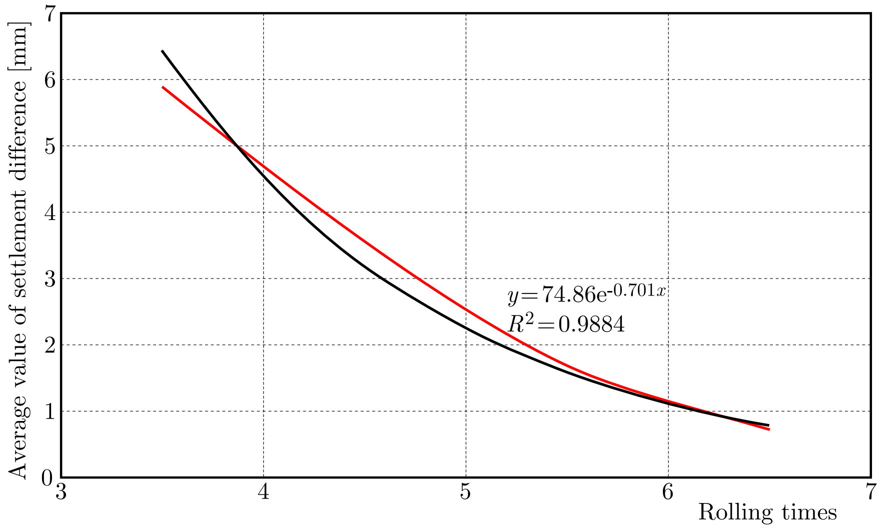

Fig. 13. Average variation trend of settlement difference with different rolling passes

Fig. 14. Coal gangue roadbed

According to the meso-remolding characteristics of coal gangue subgrade particles and rolling quality control principle, in the optimal rolling process of static pressure, the vibration compaction increased four times and the static pressure twice. It ensures the construction effect of the on-site coal gangue subgrade and provides a theoretical basis and technical support for quality control.

6. Conclusions

- Based on the basic theory and method of particle flow and with the help of a computer program, a three-dimensional coal gangue particle model with specific gradation was established to carry out the dynamic evolution process of "core retention" of the coal gangue particle crushing under stress. The gradation evolution law of the model after particle continuous crushing and the corresponding micromechanical characteristics were analyzed.

- At the meso-level, the particle displacement showed characteristics of uneven and staggered distribution, which revealed a highly complex deformation phenomenon of bulk materials under an external load.
- On the qualitative level, the static compaction process of coal gangue samples can be roughly divided into three stages: initial compaction stage, compaction and crushing stage, crushing (compaction) stage. When the axial strain is 12%, the coal gangue sample begins to break, and with the increasing axial strain, the breakage rate of the coal gangue sample rises rapidly, indicating that the breakage degree of the coal gangue sample gradually strengthens.
- The maximum contact force in the gangue sample model was about 4100 N, but most of the normal contact force value was below 900 N (accounting for about 90%), which reflects the highly uneven force chain network of bulk samples. Similarly, the maximum value of the tangential force was about 1750 N, but most of the tangential force was below 350 N. In general, in the force chain network of the coal gangue sample, the normal force value is much larger than the tangential force, which also demonstrates the basic view that the compression is mainly in the process of confined unidirectional compression.
- According to the meso-remolding characteristics of the coal gangue subgrade particles and the rolling quality control principle, in the optimal rolling process of static pressure, the vibration compaction increase four times and the static pressure twice. It ensures the construction effect of the on-site coal gangue subgrade and provides theoretical basis and technical support for quality control.

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